Case studies of Physics graduates' personal theories of evolution

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Abstract

This paper reports an interview case study with two physics doctoral students designed to explore their conceptions about the theory of evolution. Analysis of interview transcripts reveals that both students mistakenly constructed a "theory of evolution by environmentally driven adaptation" instead of the commonly accepted "theory of evolution by natural selection and random genetic changes" based on similar Lamarckian misconceptions shared by many contemporary high school and college students. Further analysis shows that their single-process "physicist" synthesis of evolution consists of the following four internally consistent misconceptions:

(1) Evolution of traits over time occurs as a result of environmentally induced and directed adaptation by organisms.
(2) The quality of traits changes gradually over generations in evolution.
(3) Acquired traits can be inherited.
(4) Variation within populations is of little significance in evolution.

Preliminary analysis suggests that a major cause of these two physics graduates' misconceptions about evolution might be their misinterpreting the scientific term "adapt" in terms of the meaning used in the everyday context. Implications for improving school biology education are discussed in light of major findings of the study.

Keywords: theory of evolution, misconception, science education.

Introduction

"Nothing in biology makes sense except in the light of evolution." (Dobzhansky, 1973, p. 125) Despite some disagreements among biologists over the intricate details about the mechanisms of evolution, it is now commonly agreed that the modern concept of evolution provides a unifying principle for understanding the history of life on earth, relationships among all living things, as well as the dependence of life on the physical environment (Rutherford & Ahlgren, 1990) and that an understanding of modern biology is incomplete without an understanding of evolution. Today, the modern neo-Darwinian synthesis of the theory of evolution, which is essentially a synthesis of

Darwin's evolution theory and Mendelian genetics that integrates both randomness and invariance into the evolutionary process (Brooks, 1983; Gould, 1980), is accepted by virtually all biologists. Due to its centrality to the overall understanding of biology and science in general, the neo-Darwinian synthesis of evolution has become such a basic and fundamental concept in science that it is regarded as common sense knowledge not only for biologists but also for scientists trained in all other areas of science.

Although it is generally believed that most scientists have at least a basic understanding of the theory of evolution, recent research in science education and the history of science suggests that it might not be the case. A review of relevant literature reveals that, contrary to popular belief, scientists, such as physicists, do not necessarily have a sound understanding of evolution and that the true nature of their common sense knowledge about evolution requires further investigation.

This paper reports an interview case study with two physics doctoral students designed to further explore these physics graduates' personal theories of evolution. Using four open-ended interview questions designed to tap students' ideas about basic concepts in evolution, this study sets out to explore these two physics graduates' conceptions about the mechanism of evolution and tries to describe, as clearly as possible, the main features of their personal theories of evolution based on in-depth analysis of their responses in the interviews. By comparing these two physics graduates' personal theories of evolution with the popular Lamarckian misconception held by many high school and college students today, this study also hopes to provide some further insights into the nature of physics graduates' common sense knowledge about the theory of evolution.

Rationale and theoretical base

Recent research in science education has shown that, due to the prevalence and persistence of some deep-rooted common sense misconceptions about the natural phenomena (such as motion, electricity, and evolution) that people developed from their intuition and past experiences, many students emerged from their study of science without a basic understanding of some elementary but fundamentally important concepts in science (McDermott, 1984). Almost without exception, studies on students' learning in science found that some deep-rooted common sense misconceptions in science held by students before entering school frequently survive high school (Bizzo, 1994; Gunstone, 1987), university undergraduate (Bishop & Anderson, 1990; Clement, 1982; Peters, 1982) and even postgraduate (Warren, 1971; Zaïm-Idrissi, Désautels, & Larochelle, 1993) science instruction and remain virtually unchanged when they leave school. Instead of acquiring a genuine, scientific understanding of basic concepts in science, students often still retain their original intuitive common sense misconceptions after years of science study at school.

One of the most striking evidences that demonstrated the prevalence and amazing persistence of some deep-rooted common sense misconceptions about basic scientific concepts in the face of formal science instruction can be found from the well-known video program on student misconceptions in science, "A Private Universe" (Schneps, 1988), which investigated college graduates' and high school students' conceptions about the causes of the seasons and some other basic concepts in astronomy. Among other things, it was found from the interviews that, regardless of their previous science education, twenty-one of the twenty-three randomly selected students, faculties and alumni of Harvard University held naive common sense misconceptions about either the causes of the seasons or the phases of the moon. Furthermore, the intuitive misconceptions held by these presumably well-educated adult students were found to be essentially the same as those held by most high school students interviewed in the same study. The fact that the majority of Harvard graduates, faculties and high school students interviewed all shared similar intuitive common sense misconceptions about the causes of the seasons regardless of their past education implies that the problem is of a more general nature, one that affects all learners in science education, including not only students but scientists as well.

Indeed, studies in the history of science have repeatedly shown that scientists were not immune to naive common sense misconceptions about fundamental concepts in science and that they were at least as resistant to changing their ideas in science as contemporary students are (Gruber, 1974, 1981; Pinch, 1985). For example, it was found that, like many students today, both Newton (Steinberg, Brown, & Clement, 1987) and Galileo (Clagett, 1959) held the popular "motion implies force" common sense misconception about the concept of force during part of their careers. Furthermore, due to their persistent commitment to this intuitive misconception, they resisted changing their ideas as long as they can, thus preventing them from developing the scientific conception about the concept of force for many years. The deep-rooted "motion implies force" misconception was so entrenched in their minds that it took Newton about twenty years to completely abandon this idea before successfully developing the appropriate scientific conception of force (Steinberg, Brown, & Clement, 1987) whereas Galileo was never able to make similar conceptual leap all his life.

Taken as a whole, the above evidences from research in science education and the history of science indicate that scientists, like all learners in science education, are susceptible to similar deep-rooted common sense misconceptions in science, which frequently prevent them from developing the appropriate scientific concepts and are highly resistant to change. Clearly, there is *no* justifiable reason to assume that scientists would necessarily have a sound understanding about most basic concepts in science, even though ideally they should know better. It may well be that scientists (such as physicists) after years of study and research within their scientific discipline, still hold some deep-rooted common sense misconceptions about basic scientific concepts outside of their field of study (such as the theory of evolution in biology) without realizing it. So, it seems reasonable to suspect that physics graduates do not necessarily have the "right" kind of common sense knowledge about the theory of evolution. Though many believe they have basic scientific understanding about evolution, some might in fact hold very naive common sense misconceptions. Further investigations, such as the one reported here, are thus needed to clarify the true nature of physics graduates' common sense knowledge about evolution.

Research design and data analysis

This study aims to explore two physics graduates' personal theories of evolution through the use of semi-structured, individual interviews, which focus on issues related to the mechanisms of evolution. Its research design and methods of data analysis are described below.

The subjects and context of interviews

The subjects of the interviews were two male physics doctoral students at a large, central Texas university. One is a 29-year-old student from India (student A); the other is a 27-year-old student from Taiwan (student B). Both students had strong background in physics and math and both were actively involved in major research projects in high-energy nuclear physics. Furthermore, both of them have previously taken at least two years of biology in either high school or universities.

All interviews were conducted during the lunch hour in the graduate student office where the students work and study, using the techniques of research on conceptual change to elicit students' genuine physicist's conceptions about evolution in the "real world" situations rather than the "correct" textbook explanations they used in the "science contest" situations. Generally speaking, the atmosphere in their (working and studying) place was casual, relaxed and intellectually demanding and thus provided an excellent environment for the students to comfortably and seriously talk about their ideas in science. To make sure they were "telling the truth," both students were told and agreed to explain their personal understanding about some interesting questions in biology without worrying about its "correctness" prior to the interview.

The semi-structured interviews, which consisted of four open-ended, free-response questions, were quite open and flexible so that students could explain their understandings and clarify their meanings fully and uninhibitedly, both before and after further thought. Whenever possible, the interviewer (the author) has tried to make sure that the four questions were asked in the same order to each student, and that students were not interrupted during their answers and further probing questions were not given until students had finished their answers to their own satisfaction. Also, the interviewer deliberately avoided using any scientific terms in the interviews, such as "evolution" and "natural selection" that might direct the students away from constructing their own explanations about evolution towards recalling the standard "correct" answers in textbooks. Each of the interviews lasted about an hour and both were audiotaped and subsequently transcribed in full by the author.

The interview questions

The interviews centered on the following four open-ended, free-response questions designed to probe students' conceptions about the topic of *evolution of traits by means of natural selection and random mutations*. Three of these questions were adapted from Brumby (1984) and Bishop & Anderson (1990). The remaining classic question on giraffes' long necks was included partly because the author was interested in finding out what his colleagues thought about the same question that baffled him before (and subsequently inspired this study).

Question 1:
How do you think giraffes develop their long necks?

Question 2:
Cheetahs (large African cats) are able to run faster than 60 miles per hour when chasing prey.
Assuming their ancestors can only run 30 miles per hour, what ideas do you have about how today's cheetahs could develop the ability to run as fast as 60 miles per hour?

Question 3:
Cave salamanders today are blind (they have eyes that are nonfunctional), though their ancestors used to be able to see.
How would you explain how blind cave salamanders today evolved from their sighted ancestors?

Question 4:
Aerosol insecticides were highly effective in killing mosquitoes when first introduced, but today, about 30 years later, they have become much less effective.
How do you think this could happen?

The first question is designed to both engage students in seriously thinking about questions related to evolution and encourage them to talk about the familiar phenomenon of evolution that they have come to know and often accept without further thought. This question also provides the most reliable information about students' initial spontaneous conceptions of evolution, which may be different from the modified and often more refined conceptions at the end of the interview.

Questions 2 and 3 are intended to reveal students' overall understandings of natural selection and the random genetic processes of mutation and sexual recombination in the neo-Darwinian synthesis of evolution from two different perspectives. Question 2 involves the improvement/appearance of a particular trait whereas question 3 involves the deterioration/disappearance of a particular trait as a result of evolution. Because successfully answering both questions requires a thorough understanding of the interplay between random genetic changes (due to mutations and sexual recombination of genes) and natural selection in the process of evolution, this pair of questions can effectively reveal students' misconceptions about natural selection and the mechanisms of evolution. For instance, they can reveal the common misconceptions held by students that the environment alone (rather than random genetic changes and natural selection) causes traits to change over time, that organisms evolve the traits they need (rather than new traits appear by chance), and that the quality of traits (rather than the proportion of individuals with certain traits) changes from one generation to the next.

The purpose of question 4 is essentially the same as that of questions 2 & 3. In addition to revealing students' misconceptions, the insecticide question is relevant to their everyday lives and serves well to check the consistency of their interpretations in different contexts.

Data analysis

Analysis of students' interview responses was done in two cyclical stages. First, the author reconstructed a tentative description of student conceptions about evolution organized around their understandings of evolution previously found problematic for many university students after formally studying evolution (Brumby, 1979, 1984; Bishop & Anderson, 1990) by identifying key concepts and phrases used by students in their interview responses. Next came the verification stage. The reconstructed description of student conceptions along with the transcript of the interview were first read and carefully checked by the student himself. Any inaccuracies and misinterpretations found were then pointed out to the author and further clarified by the student in follow-up interviews. Following the interview, a new cycle of reconstruction (revision) and verification began and it continued until a student-approved true description of student conceptions was finally achieved. The validated descriptions of student conceptions were further analyzed and compared with the corresponding scientific conceptions to determine the nature of their understandings/misunderstandings about natural selection and the mechanism of evolution.

Results of the interviews

Transcript of interview A

Interviewer: Have you ever seen real giraffes before?

Student A: Sure!

Interviewer: Have you noticed that most giraffes have very long necks?

Student A: Sure!

Interviewer: Have you thought about it? I mean why do you think they have such...(interrupted by A)

Student A: Well...uh, I have looked at the...the...science magazine said things like that.

Interviewer: Excuse me. Please make sure to tell me only what you really believe out of what you have read in these magazines.

Student A: Well, it is very possible that, you see giraffes...uh...lived in parts of Africa where you have little grass on the grounds and trees and something like that. Might be because of evolutionary pressures that...uh...long necks let the animals feed off the trees.

Interviewer: You talked about evolutionary pressure, can you explain more clearly about what you mean by that? I'm not quite sure about that.

Student A: OK, what I am trying to say is the following. Uh, modern time giraffes are found in parts of Africa where, uh, it's essentially a dry area, where there is little grass on the grounds but a good number of trees which have most of the foliage on the top parts. (The interviewer nodded and said: OK!) So, uh, it is conceivable that maybe...uh...maybe...uh...you know giraffes may have started out with shorter necks, but because they have to adapt to living in the place with little grass and tall trees, they need long necks so that they can get to the leaves.

Interviewer: You said something about giraffes adapt to the living environment, can you tell me in more detail how that happens?

Student A: That's what I have been saying. It's a question of evolution. It is very possible that giraffes may have started out with shorter necks, but since the climate change and the land is dried, they found the need to live on the leaves of the trees. They started slowly developing longer necks.

Interviewer: Can you say more about how they develop the longer necks you've talked about?

Student A: Well, because they need longer necks to reach their food, they...uh...somehow managed to use their necks to reach the trees.

	Gradually their necks became longer and longer over each generation.
(talking about Chinese food and Indian food while eating our lunch)	
Interviewer:	Have you heard about cheetahs before? Or have you seen them on TV? It's a big African cat.
Student A:	Uh, I guess so but I am not sure. How do you spell it?
Interviewer:	C-h-e-e-t-a-h.
Student A:	Right! I think it's the fastest animal in the world, right?
Interviewer:	That's right. I've seen them on a TV program called Nature. According to Nature, they can run as fast as 60 miles per hour when chasing prey.
Student A:	Yeah, I have read about that somewhere.
Interviewer:	My question is: is it possible its ancestor...their ancestors can not run as fast, say they can only run 30 miles per hour?
Student A:	Uh...well, that's a...that's an interesting question. (smiling)
Interviewer:	Is it possible?
Student A:	Well, it depends...I mean...well, maybe!
Interviewer:	OK, if we assume it is possible, how do you think this could happen? I mean, do you have any idea about how today's cheetahs could develop the ability to run as fast as 60 miles per hour?
Student A:	Uh...that's a good question. Uh-ha (smiling)...uh...uh...well, I guess to...to...to...uh...chase the prey I guess. Uh...uh...I guess to chase the prey.
Interviewer:	OK, you told me they need to run fast to survive, can you tell me how could they do that? How do they develop such ability?
Student A:	Well, how do they get such ability? Well, again if you if you...uh...there is something in the theory of evolution it says that something about acquired characteristics and something like that. That is...uh...that is...uh...if an organism finds that it has to do something...then...uh... then...uh...because of certain environmental pressure and stuff like that, it develops characteristics which is slowly over a period of time which is almost negligible. I mean, it's...went back to our business of giraffes...uh...uh...it's like they had to adapt to the situation where less grass was on the ground and more trees and...uh...they slowly developed the characteristics in order to survive.
Interviewer:	So they run faster and faster each generation?

Student A: Right, something like that maybe.

Interviewer: Are you saying that because of the environmental pressure, they will acquire the characteristics they need to survive?

Student A: Right! I mean it's again I mean it's...the...the...basic example to explain that would be the fact that...uh...something I've seen in a movie...uh...I'm not sure about the time...uh...something like 20 years ago. The world health organization claimed that they had eliminated malaria from all parts of the world. (the interviewer nodded and showed much interest) Because they came up with all sorts of chemicals which...uh...would kill out the mosquitoes, the larva and things like that. But, then...uh...in the middle eighties, there have been outbreaks of small epidemic of malaria in parts of Asia and Africa. Biologists and medical people who have gone to study the bacteria for the malaria, they found that these are essentially new strands of bacteria, which are completely resistant to the chemicals which used to kill them out before.

Interviewer: Very interesting! How do you think this could happen?

Student A: Well, they claimed that, people who worked in the team, they claimed that it's again because of this...uh...because of the essential underlying philosophy of the theory of evolution. That an organism finds it has to...there is something which is affecting its uh...its normal mode of living, it will do something to get around it. And that's essentially what the bacteria have done, they develop some characteristics which enable them to completely defy these chemicals which used to kill them out before. Since the bacteria is like a single-cell creature, it takes a short period of time to change. But for infinitely more complicated organisms, like giraffes and cheetahs, this process of change will take a long period of time. So that in a finite lifetime of ours, one could not tell the difference it has made. It might take thousands of years for this to happen.

(Chatting and eating)

Interviewer: The next question is unusual but interesting. (showing student A a picture of cave salamanders along with a brief description in a dictionary) Cave salamanders today are blind. They have eyes but their eyes are not functional. According to biologists, their ancestors used to be able to see. Can you explain how blind salamanders today evolved from their ancestors?

Student A: Well, again you see...uh...sometime in the past ancestors of salamanders...uh... there is something in the evolution biology that...uh...if organism because of change of situation finds itself in a situation in which it really doesn't need a part of its body, then...uh...I mean the physical thing might be there it may just not use it anymore.

Interviewer: OK, you just said they don't need the eyes, but how do they become blind?

Student A: Again, as I said, there is something in evolution biology that tries to explain this and said that over a period of time, an organism finds that it really doesn't need an organ of its body and...uh...physically that organ might be there but the organism might just not use it. Like in this case, we have the eyes but the eyes are useless and become blind.

Interviewer: It's really nice talking to you. Thanks a lot for your time.

Transcript of interview B

Interviewer: Have you ever seen giraffes before?

Student B: Yes, I have.

Interviewer: Have you noticed that most giraffes have very long necks?

Student B: Right.

Interviewer: Have you thought about how giraffes developed such long necks?

Student B: Uh...perhaps it's because...(pause)...giraffes may started out being not as tall, they had mild temperament and not equipped to fight with other animals for food, they didn't have horns, sharp teeth or something like that. Maybe because of this, most of the grass on the ground was occupied by other animals, in order to survive, they managed to stretch their necks to reach the leaves on the trees. My argument is based on the theory of evolution. I think maybe it is for this reason that giraffes' necks became longer and longer.

Interviewer: You have just told me why giraffes have long necks and also touched on how they did that. But you said very little about "how", can you explain more clearly about how giraffes got their long necks?

Student B: Uh...(a short pause)...perhaps giraffes didn't have such long necks in the beginning, they may have somehow stretched their bodies to reach the trees because they needed to. Notice that giraffes not only have long necks but they also have long legs. (the interviewer nodded) They tried hard to stretch their bodies towards higher trees, as a result, their necks became longer and longer over each generation.

Interviewer: OK. Have you ever heard about cheetahs or seen them on TV?

Student B: No.

Interviewer: OK. Let me show you what they look like (showing student B a picture of cheetahs along with a brief description in a dictionary). They said cheetahs are the fastest animals in the world. They can run as fast as 60 miles per hour when chasing prey. My question is: is it possible their ancestors long ago can only run 30 miles per hour?

Student B: Yes, it's possible.

Interviewer: If this is true, do you have any ideas about how today's cheetahs could develop the ability to run so fast?

Student B: Because...this is similar to the giraffe's case. In fact, the human beings are similar, too. For instance, the Olympic records in sports keep improving. Since everyone wants to break the world records, people receive intensive training and force themselves to overcome the obstacles. Of course, it will become more and more difficult to break the records because there is a limit to it. In cheetahs' case, there is a pressure forcing them to run fast in order to survive. They did their best to run fast in order to catch the prey, and slowly they developed the ability to run faster and faster over each generation.

Interviewer: The next question is about an interesting creature called cave salamanders. (showing student B a picture of cave salamanders along with a brief description in a dictionary) Cave salamanders today are blind, though they have eyes they can not see. However, biologists said their ancestors used to be able to see with their eyes. How would you explain how today's blind cave salamanders evolved from their ancestors?

Student B: Uh...it's again a question of the theory of evolution. All these cases are similar. We know human beings evolved from the ape, however, the tails of the apes disappeared in the process. Since human beings left forests, we no longer needed the tails. Similarly, cave salamanders always lived in the caves, they didn't need their eyes anymore. Uh...this is also evolution, only in an opposite direction. Because they didn't need the eyes, the eyes disappeared.

Interviewer: But their eyes are still there, right?

Student B: Right. Since they didn't need to see, they almost never used their eyes. After a long time, their eyes gradually lose their function. But their eyes are still there, it's just that they can not see things. Perhaps, after a few thousand years, even their eyes will disappear. (giggling)

Interviewer: Interesting! Have you ever used aerosol insecticides to kill mosquitoes before?

Student B: Yes.

Interviewer: Did you notice that at first they were very effective in killing mosquitoes, but they became less and less effective after you used the same insecticides for a long time?

Student B: Yes, I did.

Interviewer: Can you explain why and how this could happen?

Student B: This is the effect of immunity. When sprayed by the insecticides, a small number of mosquitoes received very little of them and may survive. They were also influenced by the insecticides, but the effect was not strong enough to kill them. Somehow these surviving mosquitoes then became immune to the insecticides. Once they had the immunity, their offspring soon inherited the ability and became resistant to the insecticides.

Interviewer: Do you mean the immunity to insecticides can be passed on to the next generation?

Student B: Right. Because something in their cells have been changed and the change can be inherited by their offspring.

Interviewer: But how did this change happen in the first place?

Student B: Uh...(pause for a moment)...uh...I don’t know...to explain this requires detailed knowledge about the structures of the specific creature and things like that. This is beyond my current understandings of biology.

Interviewer: That’s fine. Let me ask you a final question. You have mentioned the theory of evolution several times today, can you tell me what is the theory of evolution in your understanding?

Student B: Uh...all creatures want to survive, in order to survive they need to adjust themselves to adapt to their living environments. If the outside environments change, they must change accordingly, otherwise they will become extinct. Of course, not all creatures can successfully develop the change they need to survive. For instance, dinosaurs didn't develop the necessary change when environments changed and became extinct.

Analysis of students' ideas

From the way they talked about evolution in the interviews, one could clearly sense that both students A & B believed that they already had a basic understanding of the theory of evolution. However, the analysis of their interview responses below showed that their understandings about (1) the mechanisms of evolution of traits over time and (2) the nature of change in evolution of traits over time were very different from those accepted by most biologists. Furthermore, their conceptions about the mechanisms of evolution and the nature of evolutionary change were found very similar to the common sense "intuitive Lamarckism" misconceptions prevalent among many university students (Bishop & Anderson, 1990; Brumby, 1984) and most secondary boys before they were taught evolution (Deadman & Kelly, 1978). The following describes some important aspects of students' conceptions about evolution by contrasting their ideas with those currently accepted by biologists.

The mechanisms of evolution of traits over time

How does evolution of traits over time come about? To answer this question, biologists recognize that there are two distinct processes influencing traits exhibited by populations over time and they are fundamentally different in cause and effect. Namely, new traits (a) originate due to random changes in genetic materials (caused by random mutation or sexual recombination) and then (b) survive or disappear as a result of selection by environmental factors (i.e., natural selection). Thus, most biologists today believe that the evolution of traits over time is caused by the combined effects of random genetic changes and natural selection.

In contrast to the scientific views, both students A & B believed that the evolution of traits over time occurs solely as a result of environmental pressures and that there is only one single process (called adaptation) in which characteristics of the species gradually change over time.

The idea of environmental pressures as the sole cause of evolutionary change in traits over time plays the central role in students' conceptions about the mechanisms of evolution of traits over time. Both students A & B invariably used environmental pressures as their sole explanation about how and why evolution of traits comes about in their responses to all interview questions. They believed that environmental pressures, rather than random genetic changes and natural selection, cause traits to change over time and claimed that *environmental pressures* exert their influences by creating a *need/no need* for organisms to develop/discard certain traits over time in order to survive.

Examples:

Student A: if an organism finds that it has to do something...then...uh...then...uh... because of certain *environmental pressure* and stuff like that, it develops characteristics which is slowly over a period of time......

Student A: Well, because they *need* longer necks to reach their food, they...uh...somehow managed to use their necks to reach the trees......

Student B: ......cave salamanders always live in the caves, they *don't need* their eyes anymore. Uh...this is also evolution, only in an opposite direction. Because they don't need the eyes then the eyes disappear.

Failing to make a distinction between the appearance of traits in a population and their survival over time and recognize the fact that the environment does not cause new traits to appear but only "select" them after their appearance, both students insisted that environmental pressures alone will require and "somehow" empower organisms to develop the needed traits over time in order to survive. When asked to explain exactly "how" the organisms acquire the needed traits for survival under environmental pressures, students often gave typical single-process Lamarckian explanations (repeated use/disuse resulted in change in traits), indicating that they believed there is only a single process in which traits of organisms gradually change over time.

Examples:

Student B: ......In cheetahs' case, there is a pressure forcing them to run fast in order to survive. They *did their best* to run fast in order to catch the prey, and slowly they developed the ability to run faster and faster over each generation.

Student A: .....over a period of time, an organism finds that it really doesn't need an organ of its body and...uh...physically that organ might be there but the organism might just *not use* it. Like in this case, we have the eyes but the eyes are useless and become blind.

In their alternative single-process accounts of the mechanism of evolution, students seemed to incorporate the two distinct processes of random genetic changes and natural selection into one single process called (by them) *adaptation*. By using the everyday meaning of this word, namely individuals respond to environmental conditions by altering their form, function or behavior through their own efforts, they frequently interpreted evolution as a purposeful and active process of *adapting to* the environment by organisms in order to survive.

Examples:

Student A: ......I mean, it's...went back to our business of giraffes...uh...uh...it's like they had to *adapt to* the situation where less grass was on the ground and more trees and...uh...they slowly developed the characteristics in order to survive.

Student B: Uh...all creatures want to survive, in order to survive they need to adjust themselves to *adapt to* their living environments. If the outside environments change, they must change accordingly, otherwise they will become extinct......

Interestingly, students' alternative interpretation of the meaning of adaptation in evolution above fits so nicely with their previous alternative conception that environmental pressures cause both the initial appearance and the subsequent development of new traits that they tend to reinforce each other. Partly due to the apparent simplicity and self-consistency of these ideas, students consistently used both of them to explain how evolution of traits comes about in answering the interview questions and in the process have successfully constructed an environmentally driven single-process misinterpretation of the mechanism of evolution of traits over time. This naive misconception about how evolution of traits over time comes about, which was found commonly held and extensively used by both students, can be summarized as follows:

> *Evolution of traits over time occurs as a result of environmentally induced and directed adaptation by organisms.*

The nature of change in evolution of traits over time

What changes in the evolution of traits over time? According to biologists, new traits arise through random, discrete genetic changes involving individual organisms. Those traits then gradually become established in a population as the proportion of individuals in a population possessing those traits grows with each succeeding generation. Therefore, it is the *proportion of individuals* in a population with discrete (adaptive) traits that gradually changes in evolution of traits over time.

Instead of attributing the evolutionary change of traits over time to the changing proportion of individuals possessing the adaptive traits, both students A & B asserted that the *quality of the adaptive traits* gradually improves/deteriorates over each generation in the process of evolution.

Examples:

Student A: Well, because they need longer necks to reach their food, they...uh...somehow managed to use their necks to reach the trees. Gradually their necks became *longer and longer* over each generation.

Student B: ......In cheetahs' case, there is a pressure forcing them to run fast in order to survive. They do their best to run fast in order to catch the prey, and slowly they can run *faster and faster* over each generation.

By assuming that the improved traits acquired by the process of "adaptation" can be passed on to the next generation (i.e. acquired traits can be inherited) and that evolution changes the traits of individuals in populations as a whole (i.e. variation within populations is of little significance in evolution), both students interpreted the evolution of traits over time as a gradual "quality-change" process in which "insects become more immune, rather than more insects become immune." (Brumby, 1984, p. 499) Their alternative conceptions concerning the nature of change in evolution of traits over time can be summarized as follows:

The quality of traits changes gradually over generations in evolution.
Acquired traits can be inherited.
Variation within populations is of little significance in evolution.

Examples:

Student A: Well, because they need longer necks to reach their food, they......managed to use their necks to reach the trees. Gradually *their necks* became longer and longer over each generation.

Student B: ...... They tried hard to stretch their bodies towards higher trees, as a result, *their necks* became longer and longer over each generation.

Summary

The above analysis clearly shows that the two physics doctoral students interviewed did not have a basic understanding about the theory of evolution. Their common sense knowledge about evolution is in fact very similar to the popular "intuitive Lamarckism" shared by many contemporary high school and college students. Instead of gaining a sound understanding of the two-process neo-Darwinian synthesis of evolution (i.e. the theory of evolution by natural selection and random genetic changes) from their previous biology education, they have constructed a deceptively simple and coherent single-process "physicist" synthesis of evolution (i.e. *the theory of evolution by environmentally driven adaptation*) consisting of the following four internally consistent and mutually supportive misconceptions.

(1) Evolution of traits over time occurs as a result of environmentally induced and directed adaptation by organisms.
(2) The quality of traits changes gradually over generations in evolution.
(3) Acquired traits can be inherited.
(4) Variation within populations is of little significance in evolution.

Discussion

Why did the two bright physics doctoral students fail to achieve a basic, scientific understanding about evolution after a lifetime of science education? Although this study did not give any conclusive answer to this question, it has provided some useful clues for solving this intriguing mystery. The following describes the author's informed guesses regarding the possible causes of the two physics graduates' misconceptions about evolution based on analysis of their interview responses.

Even though the author has avoided using any scientific jargon in asking the interview questions, both students A & B spontaneously used such scientific terms as the *theory of evolution*, *acquired characteristics*, and *adaptation* in their responses. However, knowing these scientific terms apparently has not helped them better understand evolution. In some cases, it actually caused more confusion than clarification. As has been alluded to previously, some of the students' misconceptions about evolution were in a large part caused by their misinterpreting the scientific term "adapt" (in an evolution context) in terms of the meaning used in the everyday context. Further analysis showed that it may well be this common sense everyday misinterpretation of the meaning of adaptation in evolution that led the students to extrapolate from changes seen within the lifetime of an individual to account for evolutionary changes seen in populations selected over many generations, thereby profoundly distorting their overall understanding of evolution.

It is worth noting that both students A & B seemed to be so comfortable with their alternative *theory of evolution by environmentally driven adaptation* that they typically gave their "wrong" answers to most interview questions with a high degree of confidence. Throughout the interviews, the students seldom felt doubts about their misinterpretation of adaptation in evolution and consistently interpreted evolution of traits over time as the result of some environmentally driven adaptation by the organisms. In some cases, they spontaneously used examples from their personal experiences and prior knowledge acquired outside of school to justify their alternative theory of evolution. For instance, student A cited an example from a movie he had seen before to justify his theory. Similarly, student B used a common sense example (humans don't have tails but their ancestors did) to support his theory. Thus, students' high confidence in their alternative theory of evolution seemed to have prevented them from detecting their existing misconceptions about adaptation and evolution.

Taken together, the above discussion exposes a very intriguing question that deserves further discussion: *What caused the students to be so confident about their misinterpretation of adaptation in evolution?*

The fact that the two physics doctoral students in this study showed much higher confidence in their misconceptions than did the secondary boys in Deadman & Kelly's (1978) study leads one to suspect that they might have developed such high confidence in their misconceptions about evolution *as a result of* their previous school biology education. Exactly how this happened is not readily clear. It may be that their previous school biology education did not help them recognize the various meanings of adaptation (and other scientific terms) used in different contexts and learn to differentiate them, but instead further reinforced their misinterpretations by unintentionally yet consistently confirming them.

That both students A & B used out-of-school examples to justify their alternative evolutionary theory indicates that the knowledge they acquired from out-of-school sources also played an important role in shaping their misunderstanding about evolution. Since the language used in the various mass media, such as movies, television programs, books and magazines, to popularize and simplify the evolutionary theory is oftentimes misleading and tends to reinforce the naive Lamarckian misconceptions (Jungwirth, 1975), it might also have unintentionally increased students' confidence in their misconceptions about evolution. Therefore, another possible cause of students' high confidence in their misunderstanding of evolution is the misleading language used in popularizing the evolutionary theory commonly found in society.

In summary, the two physics students' misinterpretation of the meaning of "adaptation" in evolution could be a major cause of their naive misconceptions about evolution. These intuitive Lamarckian misconceptions were then reinforced and firmly established in the students' minds as a result of the failure of formal school biology education in helping them become aware of their misinterpretation of adaptation in evolution and the success of the misleading language used in various mass media and many out-of-school information sources in constantly confirming and reinforcing such misunderstanding.

Conclusion and implications

Taken as a whole, this study reveals that, contrary to popular belief, the two physics doctoral students interviewed did *not* have a basic understanding about the theory of evolution. Their common sense knowledge about the theory of evolution is, in many respects, very similar to the popular "intuitive Lamarckism" shared by many contemporary high school and college students. Instead of gaining a sound understanding about the two-process neo-Darwinian synthesis of evolution (the theory of evolution by natural selection and random genetic changes) from their previous biology education, they managed to construct a deceptively simple and coherent single-process "physicist" synthesis of evolution (*the theory of evolution by environmentally driven adaptation*) consisting of the following four internally consistent misconceptions.

(1) Evolution of traits over time occurs as a result of environmentally induced and directed adaptation by organisms.
(2) The quality of traits changes gradually over generations in evolution.
(3) Acquired traits can be inherited.
(4) Variation within populations is of little significance in evolution.

The above finding echoes the earlier finding of a large-scale survey study by Showers (1993) that scientists (such as physicists) often do not have adequate knowledge about basic scientific concepts (such as evolution) outside their area of professional expertise. Together, these findings signal the failure of formal school biology education in helping contemporary physics students achieve genuine scientific understanding of evolution which, according to Rutherford & Ahlgren (1990), is one of the basic and fundamental concepts in science outside of physics that all scientific literate persons must understand.

Since, as discussed earlier, the principal obstacle that prevents the students from developing a genuine scientific understanding of evolution is their *lack of awareness* of their existing misconceptions about adaptation and evolution, a potentially effective way to improve the situation is to help students recognize and unlearn their misunderstanding about evolution through conceptual change teaching in formal school biology education. For instance, one can use the various techniques of conceptual change teaching (see Hewson, 1992) to help students recognize the inadequacy of their misinterpretation of the meaning of "adaptation" in evolution through personal reflection and discussion, evaluate and differentiate its various meanings in different contexts and revise/discard their current interpretation accordingly. While there is no guarantee that conceptual change teaching will help students arrive at the desired scientific view of evolution, it could at least help them *become aware of* the inadequacy of their existing misconceptions about evolution and seriously consider adopting other alternatives.

Finally, it is important to note that the inability of conceptual change teaching to make all students arrive at the modern scientific view of evolution must not be considered as a serious defect. After all, as Richard Peters (1966) once reminded us, the aim of education is not to make all students arrive at a particular view without thinking but to help them travel, *rationally and knowingly*, with a reasonable view.

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